

Explicit Dynamic Frontal Crash Test Analysis of FSAE Roll Cage Using AISI 4130 and Docol R8 Steel

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Abstract- This study investigates the crashworthiness performance of a FSAE roll cage subjected to frontal impact using explicit dynamic simulation. Two high-strength materials, AISI 4130 chromoly steel and Docol R8 advanced high-strength steel, were evaluated. The roll cage geometry was modelled using SolidWorks and imported into ANSYS Explicit Dynamics for frontal crash simulation at an impact velocity of 8 m/s against a rigid wall boundary condition. Key performance indicators such as total deformation, equivalent von-Mises stress distribution, plastic strain, and energy absorption characteristics were analysed. A comparative study between both materials was conducted to determine structural safety performance and weight optimization potential. Results indicate that Docol R8 provides improved strength-to-weight performance compared to AISI 4130, demonstrating its suitability as an alternative roll cage material for Formula Student vehicles.

Keywords- Formula student, Roll cage, Explicit dynamics, Crashworthiness, AISI 4130, Docol r8, Ansys, Frontal impact analysis.

I. INTRODUCTION

The roll cage is the primary safety structure of a Formula Student vehicle and plays a critical role in protecting the driver during impact events. It is designed to maintain structural integrity under various crash scenarios by absorbing impact energy and preventing excessive deformation in the driver survival space. Since Formula Student vehicles operate at high acceleration and braking conditions with lightweight structural configurations, the roll cage must provide maximum strength while maintaining minimum possible weight. Therefore, proper material selection and structural validation through numerical simulation have become essential aspects of roll cage design in modern student race vehicles.

Among different crash conditions encountered during vehicle operation, frontal impact is considered one of the most critical loading scenarios due to the large amount of kinetic energy transferred to the structure within a very short duration of time. During frontal collision events, the forward members of the roll cage experience severe compressive and bending loads which may lead to structural failure if not properly designed. Ensuring

that deformation remains within allowable limits during such events is essential for maintaining driver safety. For this reason, frontal crashworthiness analysis has become a key requirement in FSAE and Formula Student vehicle structural validation processes.

Traditionally, AISI 4130 chromoly steel has been widely used as the preferred material for roll cage construction in Formula

Student vehicles due to its favorable mechanical properties such as high strength-to-weight ratio, good weldability, and reliable performance under dynamic loading conditions. The material also satisfies the safety regulations specified in Formula Student rulebooks, which further contributes to its widespread adoption across student race vehicle teams. However, increasing demand for improved structural efficiency and weight optimization has encouraged researchers and automotive engineers to investigate alternative high-strength materials capable of providing better crash performance while reducing overall vehicle mass.

Recent advancements in automotive structural materials have introduced Advanced High Strength Steels (AHSS), which offer significantly higher yield strength compared to conventional chromoly steels. Among these materials, Docol R8 steel has gained attention in automotive safety applications due to its superior strength characteristics and enhanced energy absorption capability during impact loading conditions. These properties make Docol R8 a potential alternative material for safety-critical structures such as roll cages used in Formula Student vehicles. Despite these advantages, the application of Docol R8 in FSAE roll cage structures has not been extensively investigated through explicit dynamic crash simulation methods.

Crashworthiness evaluation using numerical simulation techniques has become an important tool in vehicle safety analysis because experimental crash testing requires high cost, specialized equipment, and complex testing procedures. Finite Element Analysis (FEA) enables engineers to predict deformation behaviour, stress distribution, and energy

absorption characteristics of structures subjected to dynamic loading conditions with high accuracy. In particular, Explicit Dynamic Analysis is widely used for solving high-speed impact problems because it efficiently captures nonlinear material behaviour, large deformation effects, and contact interactions occurring during crash events. Therefore, explicit dynamic simulation provides a reliable platform for evaluating the structural safety performance of roll cage systems during frontal impact scenarios.

Several researchers have performed crashworthiness analysis of Formula Student roll cages using different simulation techniques to evaluate structural response under impact loading conditions. These studies primarily focused on validating roll cage performance using conventional materials such as AISI 4130 steel and mild steel. However, limited research has been conducted on evaluating the crash performance of Advanced High Strength Steels such as Docol R8 in FSAE roll cage applications. As a result, there exists a research gap in identifying whether Docol R8 can serve as a suitable alternative material for improving structural safety and reducing overall roll cage weight.

In addition to structural strength requirements, weight reduction plays a significant role in improving overall vehicle performance in Formula Student competitions. A lighter roll cage contributes to better acceleration, improved handling characteristics, and enhanced fuel efficiency while still maintaining driver safety. Therefore, selecting a material that provides both improved crash resistance and reduced structural weight is essential for optimizing vehicle performance. This motivates the need for comparative crashworthiness evaluation between conventional chromoly steel and advanced high-strength steel materials.

In this study, a FSAE roll cage structure is designed using SolidWorks weldment modelling methodology according to standard competition safety guidelines. The developed roll cage geometry is then imported into ANSYS Explicit Dynamics environment to perform frontal crash simulation using rigid wall boundary conditions. Two different materials, namely AISI 4130 chromoly steel and Docol R8 advanced high-strength steel, are assigned to the roll cage structure separately in order to evaluate their structural response under identical impact conditions. The crash performance comparison is carried out based on key parameters such as total deformation, equivalent von Mises stress distribution, plastic strain behaviour, and energy absorption capability during frontal impact loading.

The objective of this work is to investigate the suitability of Docol R8 as an alternative material for FSAE roll cage applications by comparing its crashworthiness performance with the traditionally used AISI 4130 steel. The results obtained

from explicit dynamic simulation provide insights into structural safety performance, material efficiency, and weight optimization potential, which can assist Formula Student vehicle designers in selecting appropriate materials for roll cage construction.

II. LITERATURE SURVEY

Roll cage structures play a critical role in protecting the driver during crash events in Formula Student vehicles and off-road competition vehicles such as BAJA and ATV platforms. Several researchers have performed structural and crashworthiness analysis of roll cages using Finite Element Analysis (FEA) techniques to evaluate their performance under different loading conditions including frontal impact, side impact, rollover conditions, and torsional loading. Numerical simulation methods are widely preferred because experimental crash testing requires significant cost and infrastructure. Therefore, virtual crash analysis has become an effective approach for validating structural safety performance before fabrication.

Mittal et al. performed explicit dynamic frontal crash analysis of an All-Terrain Vehicle roll cage using ANSYS Explicit Dynamics to evaluate driver safety during high-impact collision conditions. Their study demonstrated that explicit dynamic simulation provides reliable prediction of deformation behaviour and stress distribution during crash events and can be effectively used for validating roll cage structural safety.

Similarly, Sati et al. conducted static and dynamic crash analysis of an ATV roll cage structure under multiple loading scenarios such as frontal impact, side impact, rear impact, and rollover conditions using ANSYS simulation tools. Their work emphasized the importance of evaluating factor of safety and structural deformation under different crash cases to ensure safe roll cage performance during vehicle operation.

III. METHODOLOGY

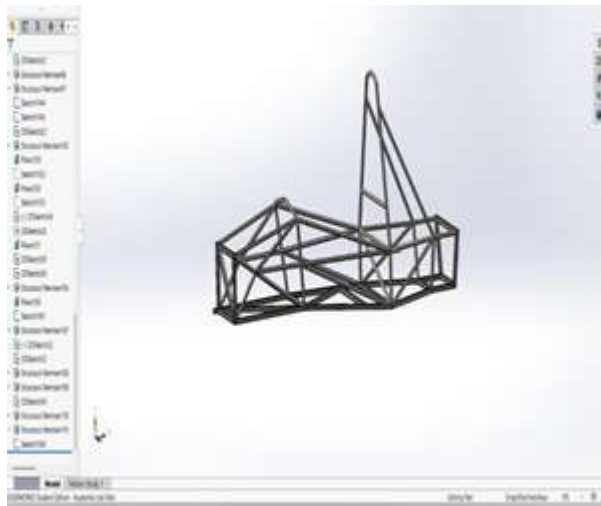
This study focuses on evaluating the crashworthiness performance of a FSAE roll cage structure subjected to frontal impact conditions using explicit dynamic simulation. A comparative analysis was performed between two high-strength structural materials, namely AISI 4130 chromoly steel and Docol R8 advanced high-strength steel. The complete simulation workflow consisted of roll cage modeling, material assignment, meshing, boundary condition definition, and explicit dynamic crash simulation.

Roll Cage Design

The roll cage geometry was developed using the weldment design methodology in SolidWorks, which is widely used for

tubular chassis modeling in Formula Student vehicle design. A 3D sketch layout approach was adopted to construct the structural members of the roll cage according to FSAE safety requirements. The weldment tool enabled accurate generation of tubular frame members while maintaining geometric continuity between structural joints.

After completion of the CAD modeling process, the roll cage geometry was exported in STEP format and imported into ANSYS Workbench for explicit dynamic crash simulation.



Material Properties

Two different materials were selected for crash performance comparison:

- AISI 4130 chromoly steel
- Docol R8 advanced high-strength steel

These materials were chosen because AISI 4130 is the conventional material used in Formula Student roll cage structures, whereas Docol R8 offers higher strength with reduced structural weight.

The mechanical properties assigned during simulation are listed below:

AISI 4130

- Density: 7850 kg/m³
- Young's Modulus: 205 GPa
- Yield Strength: 460 MPa
- Ultimate Strength: 560 MPa
- Poisson's Ratio: 0.29

Docol R8

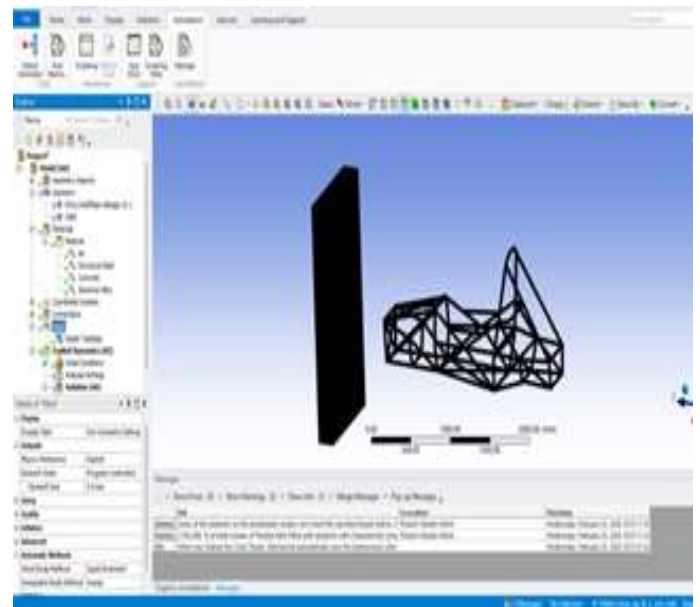
- Density: 7850 kg/m³
- Young's Modulus: 210 GPa
- Yield Strength: 690 MPa
- Ultimate Strength: 800 MPa
- Poisson's Ratio: 0.30

Meshing of Roll Cage Model

The roll cage structure was discretized using finite element meshing within the ANSYS Explicit Dynamics environment to capture structural response under high-speed impact loading conditions.

The generated mesh consisted of:

Number of nodes: 30,598 Number of elements: 38,337
Proper mesh resolution was ensured to accurately capture deformation behavior and stress distribution during frontal impact simulation.



Boundary Conditions and Impact Setup

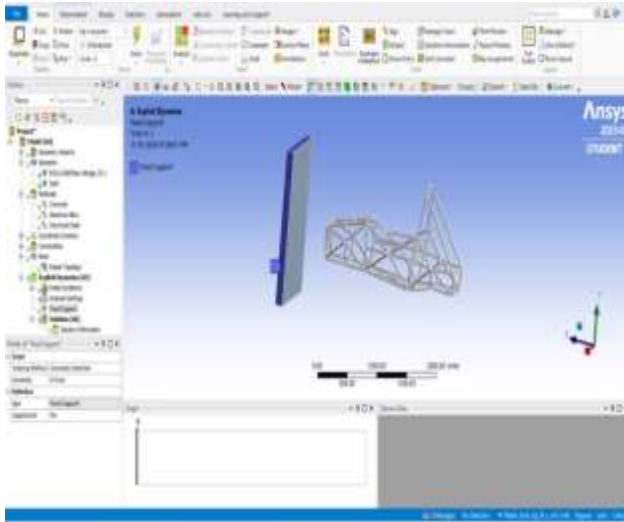
Explicit dynamic frontal crash simulation was performed by assigning an initial velocity to the roll cage structure along the longitudinal direction toward a rigid wall boundary condition. Simulation parameters used in the analysis include: Impact velocity: 8 m/s (28.8 km/h)

Impact direction: Z-axis **Boundary condition:** Rigid wall
Simulation end time: 0.003 seconds

The rigid wall condition represents a worst-case frontal collision scenario and enables evaluation of roll cage deformation characteristics under high-energy impact loading conditions.

Explicit Dynamic Simulation Procedure

The frontal crash simulation was performed using the Explicit Dynamics solver available in ANSYS Workbench, which is suitable for analyzing nonlinear transient problems involving large deformation and high-speed impact conditions.



The simulation workflow followed in this study is summarized below:

- Total deformation
- Equivalent von Mises stress
- Plastic strain distribution

These parameters were used to compare the structural response of AISI 4130 and Docol R8 roll cage configurations under identical frontal impact conditions.

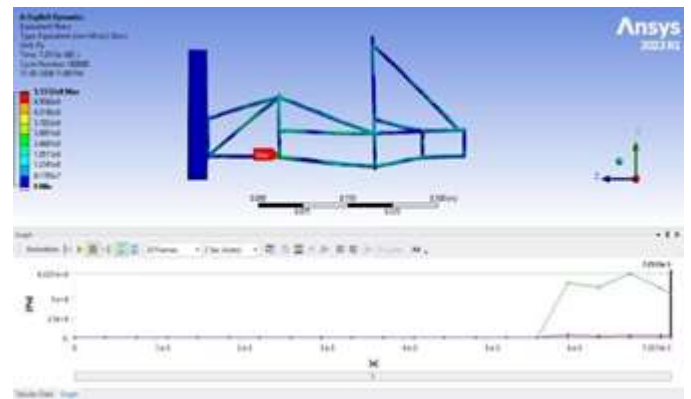
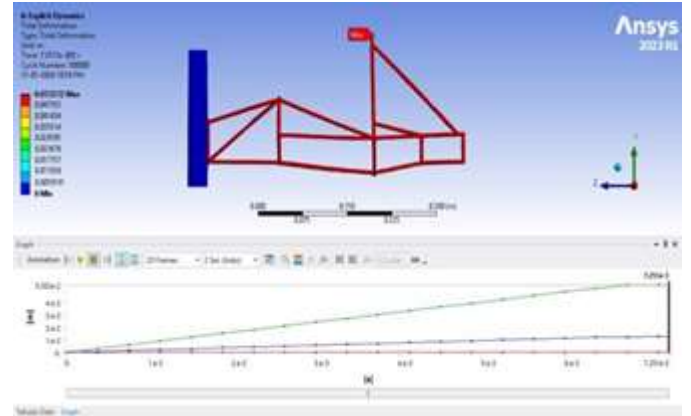
IV. RESULTS AND DISCUSSION

The explicit dynamic frontal impact analysis of the Formula Bharat roll cage was carried out at an impact velocity of 8 m/s (28.8 km/h) using two materials, namely AISI 4130 and Docol R8. The performance of the roll cage was evaluated based on total deformation, equivalent (von Mises) stress, and equivalent strain.

Total Deformation

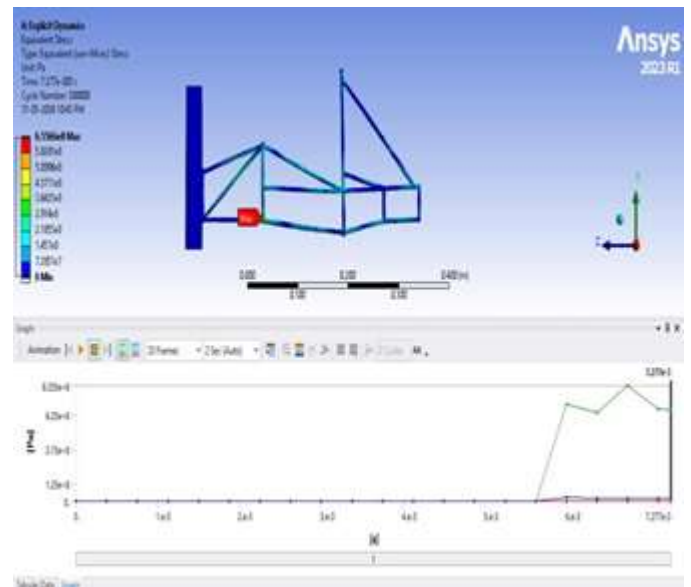
The total deformation results indicate that both materials exhibit similar structural behaviour under frontal impact conditions. The maximum deformation observed for AISI 4130 is 0.053185 m, while Docol R8 shows a slightly higher deformation of 0.053272 m.

The deformation is primarily concentrated in the frontal region and upper members of the roll cage, which are directly subjected to impact loading. The difference in deformation between the two materials is minimal (0.000087 m) and can be considered negligible. This indicates that both materials provide comparable stiffness and structural integrity under the given loading conditions.

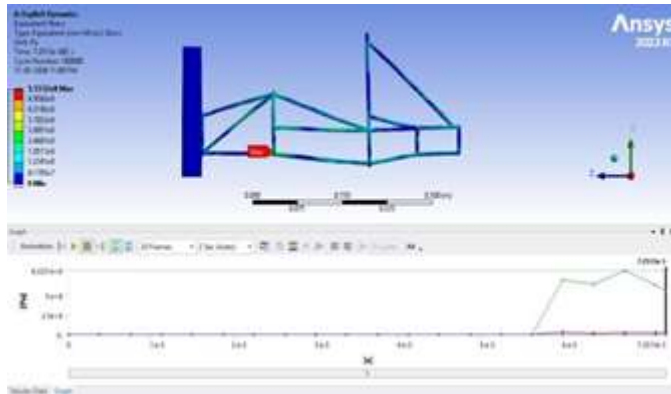


Equivalent Stress

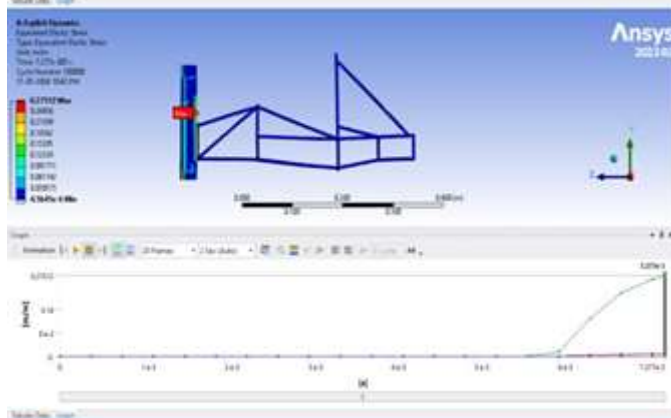
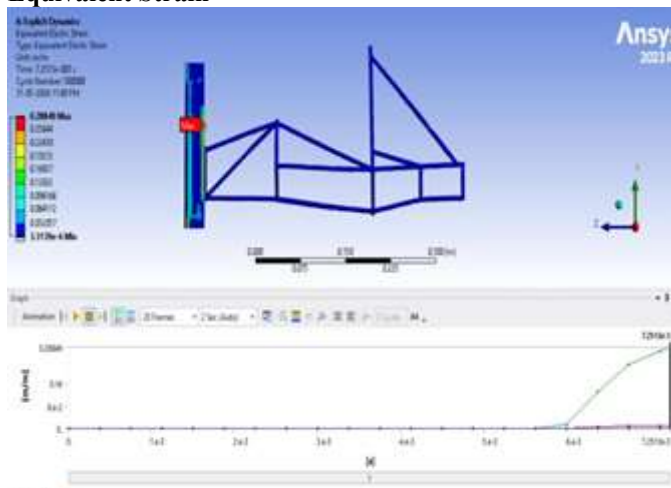
The equivalent stress distribution reveals a significant difference in the performance of the two materials. The maximum stress developed in AISI 4130 is 655.56 MPa, whereas for Docol R8 it is 555.32 MPa.



When compared with their respective yield strengths (460 MPa for AISI 4130 and 690 MPa for Docol R8), it is observed that AISI 4130 exceeds its yield limit, indicating the possibility of plastic deformation and structural failure. In contrast, Docol R8 remains within its elastic limit, demonstrating superior load-carrying capacity and improved safety performance under impact conditions vehicle performance, fuel efficiency, and handling characteristics.



Equivalent Strain



The equivalent strain results show that AISI 4130 experiences a maximum strain of 0.27512, while Docol R8 exhibits a slightly higher strain value of 0.28849. The higher strain observed in Docol R8 indicates better ductility and an enhanced ability to undergo plastic deformation without sudden failure. This characteristic is desirable in crash scenarios, as it allows the structure to absorb more impact energy, thereby improving crashworthiness and driver protection.

Weight Consideration

The total mass of the roll cage made from AISI 4130 is 44 kg, whereas the roll cage fabricated using Docol R8 weighs 41 kg. This represents a weight reduction of approximately 3kg, which contributes to improved

Overall Discussion

From the comparative analysis, it is evident that both materials provide similar deformation characteristics. However, Docol R8 demonstrates superior performance in terms of stress handling and ductility while also offering a reduction in weight.

Although AISI 4130 is traditionally used in roll cage design, the results indicate that it may not perform as effectively under high-impact conditions due to stress exceeding its yield strength. On the other hand, Docol R8 exhibits better crashworthiness by maintaining stress within allowable limits and providing improved energy absorption capability.

V. CONCLUSION

The present study focused on the explicit dynamic frontal impact analysis of a Formula Bharat roll cage using two different materials, AISI 4130 and Docol R8, at an impact velocity of 8 m/s. The performance of both materials was evaluated based on key crashworthiness parameters such as total deformation, equivalent stress, and equivalent strain.

The results indicate that both materials exhibit nearly identical deformation behavior, confirming comparable structural stiffness under the applied loading conditions. However, a significant difference is observed in stress distribution, where AISI 4130 exceeds its yield strength, indicating potential structural failure, while Docol R8 remains within its elastic limit, ensuring better structural safety.

Furthermore, the equivalent strain results show that Docol R8 possesses higher ductility, allowing it to undergo greater plastic deformation and absorb more impact energy without sudden failure. This characteristic enhances the crashworthiness of the roll cage and contributes to improved driver protection.

In addition, the roll cage fabricated using Docol R8 shows a reduction in weight compared to AISI 4130, which is advantageous for overall vehicle performance and efficiency.

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